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# Decision Analysis Framework for Evaluating CTBT* Seismic Verification Options

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September 1986





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# DECISION ANALYSIS FRAMEWORK FOR EVALUATING CTBT* SEISMIC VERIFICATION OPTIONS

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ABSTRACT

This report describes a decision analysis framework for evaluating seismic verification options for a Comprehensive Test Ban Treaty (CTBT). In addition to providing policy makers with insights into the relative merits of different options, the framework is intended to assist in formulating and evaluating political decisions--such as responses to evidence of violations--and in setting research priorities related to the options. To provide these broad analytical capabilities to decision makers, the framework incorporates a wide variety of issues. These include seismic monitoring capabilities, evasion possibilities, evidence produced by seismic systems, U.S. response to the evidence, the dependence between U.S. and Soviet decision-making, and the relative values of possible outcomes to the U.S. and the Soviet Union. An added benefit of the framework is its potential use to improve communication about these CTBT verification issues among U.S. experts and decision makers. The framework has been implemented on a portable microcomputer to facilitate this communication through demonstration and rapid evaluation of alternative judgments and policy choices.

The report presents the framework and its application in four parts. The first part describes the decision analysis framework and the types of analytical results produced. In the second part, the framework is used to evaluate representative seismic verification options. The third part describes the results of sensitivity analyses that determine the relative importance of the uncertainties or subjective judgments that influence the evaluation of the options. The fourth (and final) part summarizes conclusions and presents implications of the sample analytical results for further research and for policy-making related to CTBT verification. The fourth section also describes the next steps in the development and use of the decision analysis framework.

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# I. INTRODUCTION

## BACKGROUND

For almost thirty years the United States, the Soviet Union, and the United Kingdom have been discussing a Comprehensive Test Ban Treaty (CTBT), which would prohibit all testing of nuclear weapons and all applications of peaceful nuclear explosions. Although the most recent round of negotiations began in 1977 and recessed in 1980, there continues to be widespread international interest in a CTBT.

The debate over the desirability of a CTBT has focused on a few key issues. Foremost is the contention that a CTBT would slow the arms race and retard nuclear proliferation. Early discussions centered on the issue of possible clandestine tests and the adequacy of verification capabilities. However, from the beginning, opponents have argued that testing is needed to provide an invulnerable deterrent (Teller, 1961), and there has always been general skepticism about a test ban treaty. This position has received more support under the Reagan administration and discussion has shifted to the value of nuclear testing in developing new weapons or testing those in the stockpile, and maintaining nuclear weapons design capability. This change in emphasis does not reflect a belief that verification issues have been solved but rather that there are differences in the priorities of the Reagan administration compared to those of previous administrations.

The emphasis one places on these issues determines the desirability of a CTBT. In fact, opposite conclusions regarding the desirability of a CTBT can often be obtained based only on different opinions about the adequacy of verification capabilities (Scribner et al. 1985).

Throughout the debate, much attention has been given to seismic verification capabilities. Existing seismic stations outside U.S. and Soviet borders can detect and identify large underground nuclear tests, but there are various ways to evade detection. For example, it is possible to detonate a low-yield (e.g., 1-kt) device deep underground within a large cavity, thereby decoupling the energy source from the medium that transmits the seismic signals to the monitoring station. This technique dramatically reduces the signal strength, thereby lessening the ability of external seismic stations to detect and identify nuclear tests. Other evasion schemes that have been discussed extensively include simulating earthquake wave forms by detonating multiple nuclear explosions appropriately distributed in space and time, and hiding the signals from the explosion in the signal of an earthquake. In-country seismic stations, because of the proximity of the station to the potential evasion site, allow the use of multiple seismic waves to detect and identify evasion attempts. While all of the evasion schemes pose challenges that must be considered when evaluating the verification capability for monitoring a CTBT, cavity decoupling poses the greatest monitoring challenge for the in-country network (Hannon 1986).

Extensive analyses of the technical performance of in-country seismic systems under a range of scenarios have been completed by Evernden (1976 a,b,c); Sykes and Evernden (1982); Hannon (1983, 1985a); Sykes, Evernden, and Cifuentes (1983); and Evernden et al. (1986). The earliest analyses were based on detection capabilities using seismic monitoring practices and frequencies (1 Hz) current at that time. The latest analysis by Evernden et al. (1986) is based on the promising possibility that monitoring at higher frequencies (up to about 30 Hz) will significantly enhance seismic detection and identification capabilities of underground explosions.

While there is lack of agreement about whether the high-frequency monitoring capability is proven or even feasible (Hannon, 1985b; Evernden, 1985), it is generally agreed that detection of fully decoupled 1 kt explosions will require an extensive in-country network of seismic stations. Hannon (1983) has estimated that 30 in-country array stations will be required to meet the 1-kt objective using conventional monitoring frequencies; Evernden et al. (1986) estimate that approximately 25 high-frequency stations will be sufficient. However, substantial differences of opinion exist as to whether such a monitoring capability can provide acceptable verification of a CTBT (Weisburd, 1985).

In addition to the uncertainties regarding seismic monitoring capabilities, there are numerous other verification-related issues. For example, there are nonseismic sources of evidence that may improve verification capabilities: e.g., intelligence information or on-site inspections. When judging the ability to verify compliance with a CTBT, the capabilities of these sources should be considered along with the capabilities of seismic systems. There are also political issues that need to be considered. These might include: how willing are we to respond to evidence of a violation, how much ambiguity in the evidence can be tolerated, and what are the implications of responding to false indications of treaty violations? A related issue is the dependence of one party's decisions to comply or to violate on perceptions of the other party's ability to detect and respond to violations.

There are also numerous value judgments that must be made when determining the adequacy of a verification system. For example, one must consider the values to the U.S. and the Soviet Union of mutual treaty compliance, successful evasion by one party or the other, exposure of actual violations, or the accusation of a violation when, in fact, the other side is complying with the treaty. Finally, the cost and intrusiveness of an effective in-country seismic system cannot be ignored.

The list of factors, uncertainties, and value judgments that must be considered is long, and the issues are complex. To make good decisions, policy makers need more than intuition. If they rely on advice from technical experts in only one area such as seismic monitoring, the policy makers may be ignoring equally important consideration of the other issues listed above, or they may be accepting implicitly a technical expert's value judgments in areas outside his or her field of expertise. If, instead, policy makers consult a variety of experts, they need an effective way to integrate the experts' information and to ensure consistent treatment of the many interrelated factors.

## EVALUATION FRAMEWORK

To help policy makers integrate facts and judgments and evaluate them effectively, we have developed an analytic framework that facilitates systematic evaluation of alternative seismic monitoring networks for a CTBT. The framework is based on decision analysis methodology. It is intended to assist policy makers in formulating and evaluating political decisions and research alternatives related to verification options.

The framework incorporates the wide variety of issues discussed above, including seismic monitoring capabilities, evasion possibilities, evidence produced by seismic systems, U.S. response to the evidence, the dependence between U.S. and Soviet decision-making, and the relative values of possible outcomes to the U.S. and the Soviet Union.

The framework can be used to quantify the effectiveness of seismic monitoring systems. We use several measures of effectiveness, including the probability of identifying a clandestine test if it occurs, the number of false alarms, the number of ambiguous (unidentified) seismic events, the appropriateness of the U.S. response to evidence, and the likelihood of deterring treaty violations. In addition, a single number--overall net value of the verification system--can be obtained by a combined weighting of the above performance measures with value and cost judgments. The value judgments include the relative importance of three broad verification goals: deterring violations, assuring timely detection if deterrence fails, and building confidence in the verification system and the treaty itself. The analysis of cost can take into account capital, operating, and research and analysis costs, as well as less tangible impacts such as the intrusiveness of in-country stations or the negotiability of some aspects of the verification system.

The primary advantages of the framework are that it provides a systematic method for investigating technical issues and integrating technical information, examining value and cost tradeoffs, and analyzing the sensitivity of results to alternative judgments on technical, value, or cost factors. Use of the framework can thereby improve communication about CTBT verification among U.S. experts and decision makers. The framework has been implemented on a portable microcomputer to allow demonstration and rapid evaluation of alternative judgments and policy choices. For technical documentation of the decision analysis computer model, see Strait and Sicherman (1986).

## REPORT ORGANIZATION

The remainder of this report describes the framework and illustrates its application to the choice among seismic verification options. We present this material in four parts. In the first part we describe the decision analysis framework and the types of analytical results produced. In the second, we apply the framework to the evaluation of representative seismic verification options and provide an illustrative evaluation of the options.

In the third section we describe the results of sensitivity analyses that determine the relative importance of the uncertainties or subjective judgments that influence the evaluation of the options. The sensitivity analysis helps to focus attention on the most important uncertainties or judgments and thereby aids policy makers in choosing research priorities and goals for negotiation. For example, the analysis described here highlights the technical and political difficulties associated with the monitoring of low-magnitude events and the importance of judging the significance of low-yield treaty violations. The analysis also provides insight into the necessity of a sound approach for interpreting and responding to evidence supplied by the monitoring system.

In the fourth (and final) section we summarize conclusions and the implications of the sample analytical results for further research and for policy-making related to CTBT verification. In this section we also describe the next steps in the development and use of the decision analysis framework and the Laboratory's current activities in that area.

## 2. DECISION ANALYSIS FRAMEWORK

Faced with choosing among seismic verification options, a policy maker should consider the wide range of interrelated factors listed above. In practice, the decision maker probably will be provided with technical data and an estimate of uncertainty for some factors, such as seismic capabilities and the type of monitoring evidence produced by various seismic systems. However, the decisions also will involve subjective judgments about factors such as: the interpretation of monitoring evidence; the impact of U.S. responses to evidence of violations; estimates of the evader's cost/benefit analyses of complying with or violating the treaty based on their perceptions of our capabilities; and, finally, the relative values of assurance, deterrence, and confidence verification goals and the costs of the options

The decision analysis framework examines each of these considerations and provides a model for incorporating all of them into the quantitative evaluation of options. This model includes factors for which technical data will be available as well as those judgments that are inherently subjective. The following paragraphs describe each component of the framework and a sampling of the type of input data required. The organization of these components and some of the interrelations among them are illustrated in Fig. 1.

### VERIFICATION SYSTEM DESCRIPTION

The verification system element of the framework is simply a description of the technical capabilities of each alternative. For example, in the illustrative application the options range from the present-day seismic detection capability to systems more capable of detecting low-magnitude events. The present-day capability is limited to national technical means (NTM), which include external (or teleseismic) monitoring stations plus intelligence-gathering sources such as satellites.

The other options considered all employ in-country seismic stations to augment current NTM capabilities. The first representative system is called a Simple network; it comprises 10 simple in-country seismic stations. The Simple network is roughly

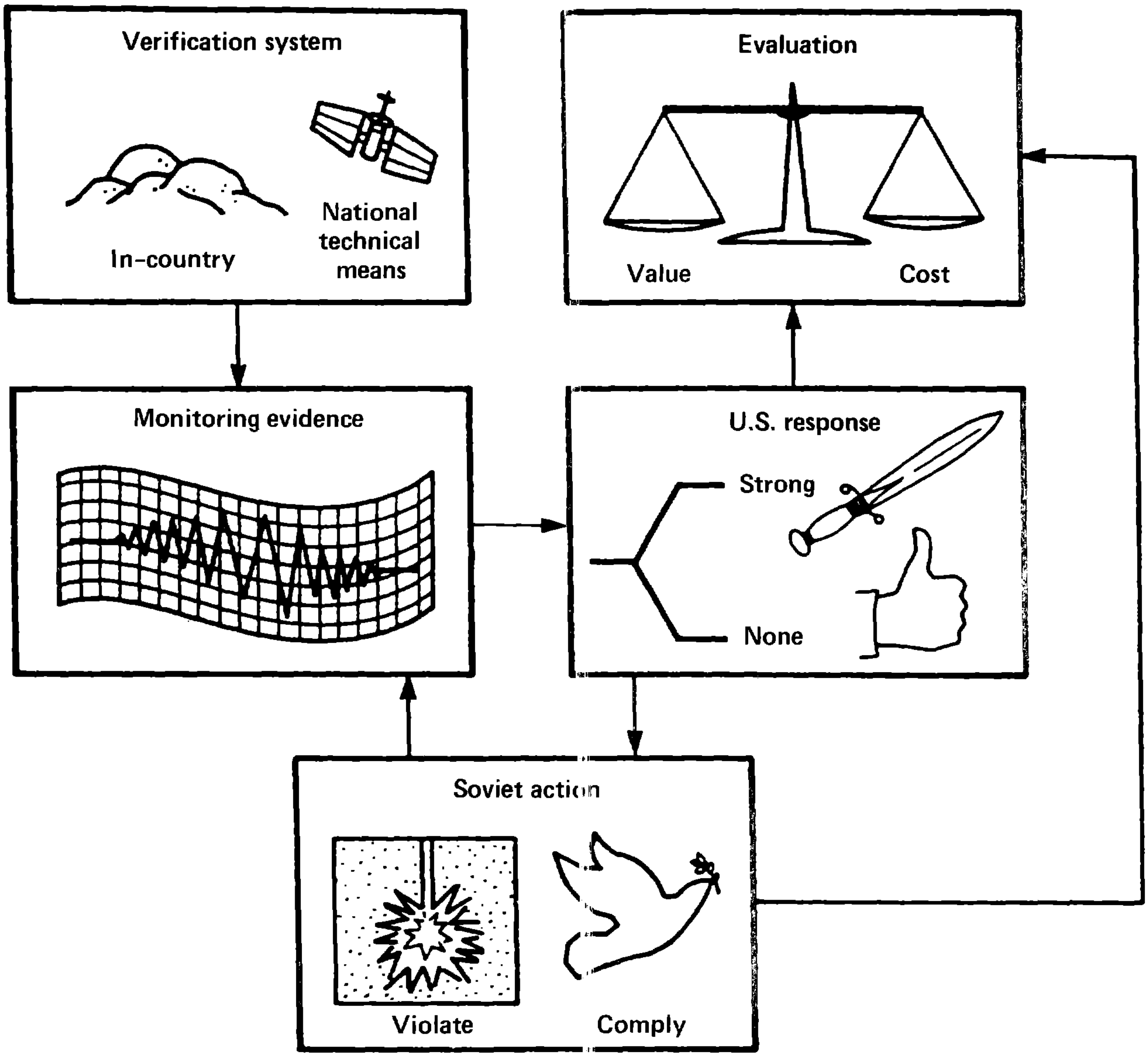


Figure 1. Major components and interrelationships in our decision analysis model for evaluating options for verifying compliance with a Comprehensive Test Ban Treaty. The model combines technical factors (e.g., detection capabilities, natural seismicity), uncertainties (e.g., Soviet action to comply or violate), and value judgments (e.g., relative merit of detecting violations vs avoiding false alarms).

equivalent to the network under discussion during the negotiations that recessed in 1980 (York, 1983). The second representative option is called the Array network; it comprises 30 in-country array-type stations. The Array network is more extensive (and therefore may be more intrusive) than the Simple network option. The arrays take advantage of the fact that data recorded at individual sensors can be combined in various ways to enhance signal-to-noise characteristics and thereby improve detection capability. Other approaches for improving the signal-to-noise ratio include using high frequencies at single borehole sites. Future networks might contain both types of stations, depending on their relative performance in specific environments and against specific evasion schemes. For purposes of this discussion, the array network can be regarded as broadly equivalent to the most capable systems currently discussed, for example, by Hannon and Evernden.

Typical verification system inputs for these three alternatives are illustrated in Fig. 2. The inputs are probabilities of detection for events of increasing magnitudes. Note that the Array system has the highest likelihood of detecting low-magnitude events. Later, we will use a single detection magnitude to represent each system; the point we will use is the median (0.5) of the probability distribution on detection magnitude. From Fig. 2 these representative points are:

| | |
|---|---|
| NTM | 3.6 |
| Simple | 3.3 |
| Array | 2.4. |

The probabilistic nature of the input reflects the inherent uncertainty in detecting seismic events of various magnitudes. To complete the description of the seismic system, detection probabilities are combined with data on the ability of the seismic system to identify whether a seismic event is an explosion or an earthquake. (This feature is also referred to as discrimination capability.)

Traditional analyses of seismic verification systems include the types of detection and identification data described above. Typically, the traditional analyses "stop here," and technical experts and policy makers are often left to intuitive consideration of the

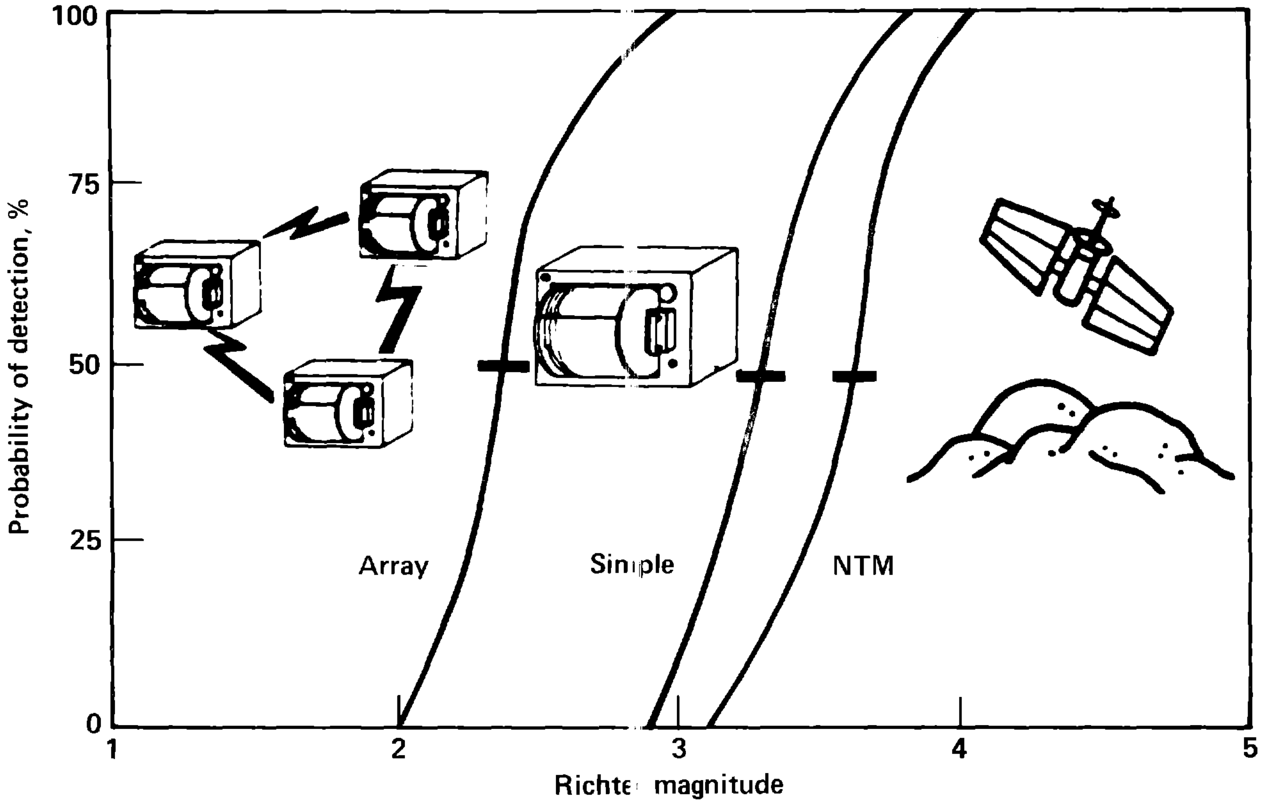


Figure 2. Illustrative input data for three verification systems. System capabilities are measured by the probability of detecting seismic events of various magnitudes anywhere in the Soviet Union. The Array system consists of a network of 30 stations inside the Soviet Union, with each station comprising an array of seismometers. The Simple system is a countrywide network connecting 10 single seismometers. The current system uses only national technical means (NTM) (satellites and seismometers located outside the Soviet Union).

wide range of additional factors represented in Fig. 1. In our framework, however, these additional factors are incorporated explicitly. For example, to complete the analysis in the verification system component, estimates of seismic detection and identification capabilities are combined with estimates of capabilities of auxiliary information sources to support (or refute) seismic evidence. Auxiliary information is assumed to be available from intelligence sources as well as from on-site inspections at locations of suspected violations.

These descriptive data on the monitoring systems are input to the monitoring evidence component. The input relationship is illustrated by the arrow in Fig. 1.

## MONITORING EVIDENCE COMPONENT

The monitoring evidence component estimates the quantity, quality, and nature of evidence produced by the seismic system (and auxiliary sources) when confronted with various seismic events in the Soviet Union. These events include natural seismic activity as well as man-made activity, such as chemical explosions and possible Soviet clandestine nuclear tests. The current model examines natural seismicity and Soviet clandestine nuclear tests. Chemical explosions could be included in future models.

Input to the monitoring evidence component includes, as stated above, estimates of natural seismic activity (frequency of events versus magnitude) and hypotheses about the number and yield of nuclear tests the Soviets might conduct if they did violate the treaty. The input data on potential Soviet tests are based on a judgment of the smallest number and yield that would be militarily or politically significant. We assume smaller numbers or yields need not be detected by the verification system. A useful feature of the model is that a single Soviet clandestine testing strategy need not be determined in advance; a variety of Soviet strategies can be entered and the model will select the best strategy from the Soviet perspective.

## U.S. RESPONSE COMPONENT

The next important consideration is how the U.S. might respond to various levels of evidence. Possible U.S. responses to persuasive evidence of violations range from strong actions to milder actions, which might be dictated by overriding political considerations. By strong action we mean, for instance, abrogating the treaty and resuming nuclear testing. In response to less convincing evidence of violation, the framework allows no U.S. response or milder actions, such as issuing a demarche.

Our framework examines this issue for two reasons: (1) because the verification system basically produces information, the best way to measure the value of the information is to examine how it can affect U.S. decisions; and (2) because we believe that Soviet actions will be influenced strongly by their perceptions of our response. For example, if the Soviets perceive that the U.S. will not respond even if the Soviet Union is caught violating the treaty, they are less likely to comply with the treaty. Similarly, the Soviets may lose the incentive to comply if they perceive that the U.S. is likely to receive false information from the seismic system and subsequently take strong but unwarranted actions based on the false information. Thus, the U.S. response component plays an important role in analyzing possible U.S. responses to monitoring evidence, and this component therefore has a major influence on the likelihood of Soviet actions to violate or comply with the treaty.

The U.S. response component has important but conceptually simple inputs. Many of these are in the realm of subjective political judgment and, because they are difficult to quantify, they are less amenable to technical analysis and validation. Inputs to this model are the likelihoods of various U.S. actions as a function of the strength of evidence produced by the seismic system and auxiliary sources. Figure 3 illustrates sample input for the U.S. response decision. The determination of an actual curve would require careful consideration by senior officials, and it would vary with the state of the relationship between the U.S. and the Soviets. Three categories of response are included: no action, strong action (such as abrogating the treaty), and mild action, which in a specific instance might mean issuing a demarche. For a given level of evidence, the probabilities of strong, mild, and no action are measured as the vertical distances as

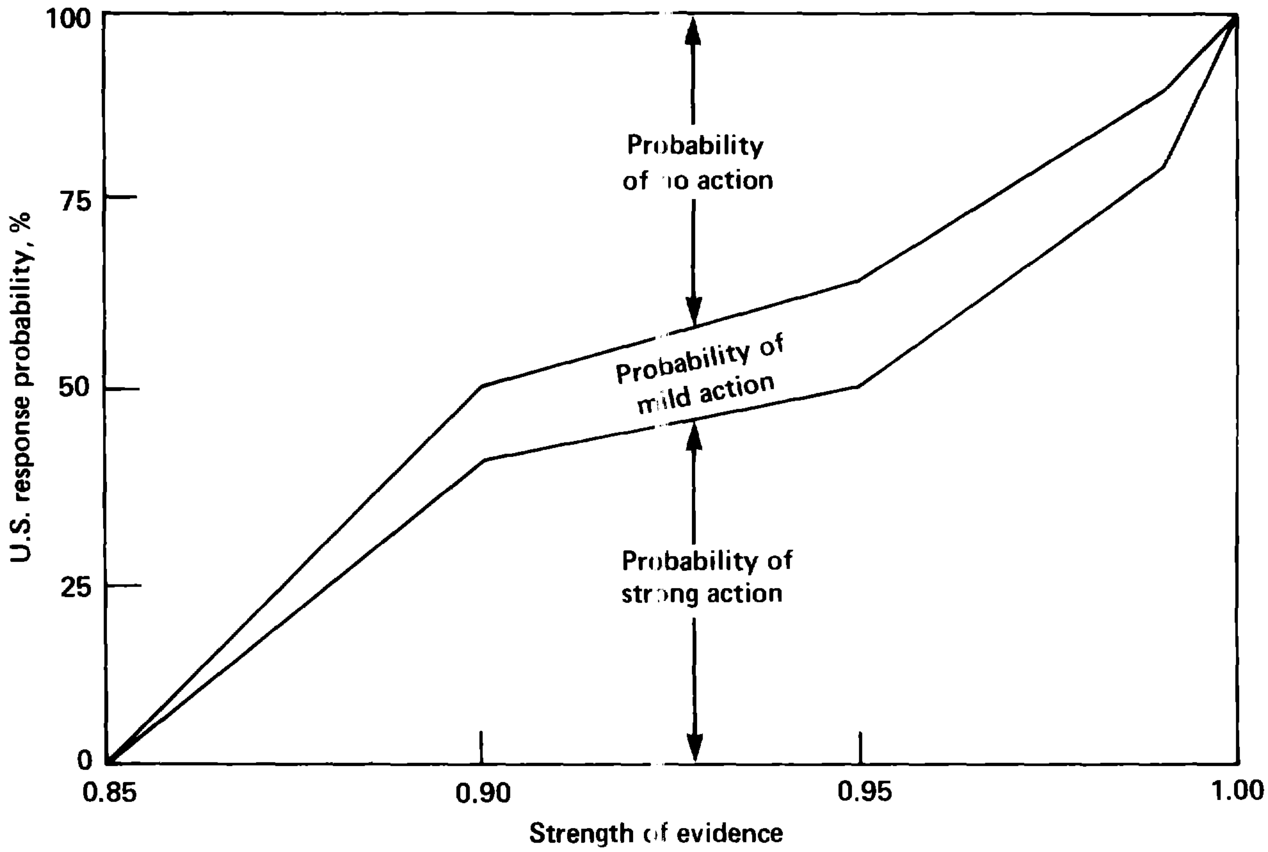


Figure 3. Sample input data for the U.S. response component of our decision analysis model. The probability of a given U.S. response depends on the strength of the evidence of treaty violations. The strength-of-evidence axis can be interpreted as the likelihood that the monitoring evidence cannot be explained by earthquakes. The probabilities of strong, mild, and no action are measured as vertical distances, as indicated on the graph. This type of judgment regarding U.S. responses is critical to the choice of a verification option.

indicated on the graph. The strength-of-evidence axis refers to evidence of a treaty violation. As we will discuss later, the method the U.S. uses to judge the strength of monitoring evidence is a crucial CTBT verification issue.

## SOVIET ACTION COMPONENT

The fourth component is the Soviet action component. As mentioned above, this component examines the likelihood of Soviet violation or compliance with the terms of the treaty. This component of the framework provides an opportunity to incorporate important judgments about Soviet behavior and thereby allows quantitative measurement of the deterrence capabilities of verification options. Although the abrogation of, or withdrawal from, a CTBT by the Soviet Union is a distinct possibility, it is not considered explicitly in our model.

Important dependencies among the monitoring evidence, U.S. response, and Soviet action components are illustrated by the arrows in Fig. 1. In fact, the relationship is interactive: Soviet actions violating or complying affect the seismic activity and the monitoring evidence and thus affect the probable U.S. response, which in turn is a factor in the Soviet decisions. The interaction is, at best, difficult to analyze, and, at worst, intractable. Nevertheless, the interaction is central to treaty verification decision-making. We believe that our model of this interaction represents a significant step forward in the ability to analyze this important verification issue.

The model of the interactions between U.S. and Soviet decisions is organized in the same order as this written description: the U.S. puts in place a seismic system to generate monitoring evidence that leads to a U.S. response. Once that system--monitoring equipment and planned responses--is in place, the Soviets assess its capabilities, along with other military and political information, and then decide whether to violate or comply with the treaty.

The primary inputs to the Soviet action component are the relative values of possible outcomes to the Soviets. Some of these values and their meanings are illustrated on the decision tree in Fig. 4.

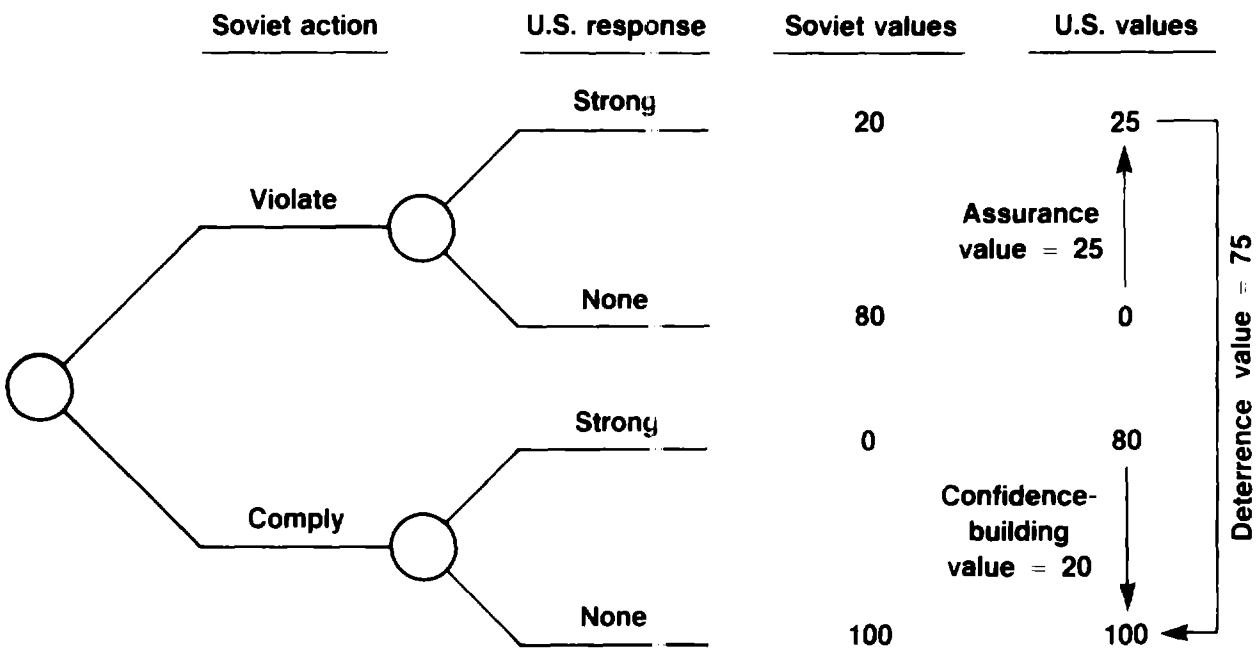


Figure 4. Probability tree with sample input value judgments for the Soviet action and evaluation components of the model. Four possible outcomes are depicted, along with illustrative relative values to the Soviet Union and the U.S. Estimates of Soviet values are critical in determining the deterrence effects of verification systems. U.S. values reflect judgments of the relative benefits of the deterrence, assurance, and confidence-building aspects of a verification system.

The tree in Fig. 4 enumerates four possible outcomes for Soviet actions and U.S. responses. The Soviets could violate or comply with the treaty; the U.S. could take strong or no action in response. (For simplicity, we have ignored the mild U.S. response.) The first column to the right of the tree shows illustrative weighting values of the importance to the Soviet Union of the four outcomes. The values reflect a judgment that the Soviets place the highest value on mutual compliance, the second highest value on successful (unchallenged) evasion of the treaty, the third highest on detection while violating the treaty, and the lowest value on being falsely accused of cheating when they are, in fact, complying. Since the false accusation is accompanied by strong U.S. action (i.e., abrogating the treaty), in the worst Soviet Union outcome the Soviets fall behind the U.S. in underground testing. These value judgments are illustrative; an important use of the model is to examine the effect of using different judgments about Soviet values.

## EVALUATION COMPONENT

The final component is shown in the upper right-hand corner of Fig. 1. Called the evaluation component, this element of the framework incorporates judgments of the relative worth of the assurance, deterrence, and confidence verification goals and the relative costs of the options.

As in the Soviet action component, a primary input to the evaluation component is the relative U.S. value attached to the same combinations of Soviet actions and U.S. responses. Illustrative values are shown in the right-hand column of Fig. 4. Note that the highest-value outcome from this U.S. perspective is assumed to be verified compliance with the treaty, and the least attractive outcome is successful (undetected) treaty violation by the Soviets.

Figure 4 also shows the correspondence of the relative values of outcomes to the three verification goals of deterrence, assurance, and confidence-building. While there are no universally accepted definitions of these terms, and therefore no single way to compute their value, the scheme shown in Fig. 4 provides one way to reflect their relative importance in the model. More importantly, this assumed relationship allows one to test the sensitivity of results to changes in the emphasis on these goals.

As shown in Fig. 4, a simple way to measure the value of assurance is by the relative increase in value when Soviet violations are detected. Similarly, the importance of confidence-building could be reflected by the increase in value when false accusations of Soviet violations are eliminated. Following this same simplified approach, the value of deterrence could be determined from the difference in U.S. values between the best outcome when the Soviet Union complies and the best outcome when they violate. The implication of this highly simplified approach is that in Fig. 4 the following weights are assigned: assurance, 25; deterrence, 75; and confidence-building, 20. Alternatively, these weights imply that the emphasis on assurance and confidence is roughly equal, while the deterrence goal is judged to be three times more important.

Taken together, these models compose the decision analysis framework. The framework considers a wide range of issues, and therefore it provides explicit and consistent means for incorporating these important factors into the evaluation of options. In addition, the framework facilitates systematic analysis of the sensitivity of the evaluation to each of these factors, thereby showing the affect of alternate assumptions and the relative importance of resolving differences of opinion.

This concludes our explanation of the decision analysis framework. In the following section, we apply the framework to the evaluation of the seismic verification options. Again, output results are discussed. However, unlike the discussion of the framework, the following section focuses on the insights produced by the analysis. Our discussion concludes with a summary of important issues to be resolved and priorities for future research.

## 3. ILLUSTRATIVE EVALUATION OF SEISMIC VERIFICATION OPTIONS

While most authorities agree that an in-country seismic network will be required for adequate verification of a CTBT, there are strongly divergent views on the required capabilities of that network, especially regarding detection of clandestine low-magnitude events. For example, Alewine (1985) argues that recent improvements have reduced signal detection thresholds and that research should continue with the goal of pushing the threshold to "as low a level as possible." In contrast, Dyson (1984) notes that every increase in low-magnitude detection sensitivity substantially increases the expected number of natural seismic events recorded. Due to the difficulties associated with sorting out clandestine tests from earthquakes, a technically superior system that lowers the threshold and, therefore, raises the detection rate of seismic events might be politically unworkable because of a higher frequency of false alarms. Making the assumption that a high false alarm rate would be much more troublesome politically than a low detection rate, Dyson suggests that seismic monitoring systems should be "as insensitive as possible."

These opposing conclusions about the optimal seismic monitoring capabilities for a CTBT reflect the complex set of tradeoffs involved in deciding what detection capability is best from the U.S. point of view. In this section we use the decision analysis framework to examine this question. We also consider two related questions:

- What factors influence the performance of a given system and thereby affect the relative values of different systems?

- In what areas of research and development are there crucial needs to resolve uncertainties or to overcome technical problems?

The example is complete in the sense that input data have been provided for all components of the framework. These data represent one view of the best estimates of current seismic monitoring capabilities. However, many of the subjective inputs related to political judgments and military testing requirements were chosen to enrich the example; these particular inputs do not necessarily reflect expertise from outside LLNL.

Our presentation of the example follows the order of Fig. 1. Verification system descriptions are the same as above: we evaluated NTM plus the in-country Simple and Array networks. We also generalized the Array network capabilities to create a hypothetical "very low-magnitude" system with median detection capability at magnitude 2.0. This was not intended to represent any specific system, but rather to provide a reference point to indicate trends estimated by the model at very low magnitudes.

MONITORING EVIDENCE

For the illustrative analysis we have assumed (1) that widespread cavity decoupling is a plausible evasion scenario and (2) that we are concerned with two alternative testing programs: one that involves many low-yield (1-3 kt) tests, and one involving a few higher-yield (5-10 kt) tests. Note that the choice of Soviet testing programs against which the verification options are judged depends on a determination of which programs are militarily or politically significant. These programs, coupled with estimates of natural seismicity in the Soviet Union, define the challenge to the monitoring systems.

Using these inputs, the verification system and monitoring evidence components of the model can be used to determine:

- Percent of militarily significant Soviet clandestine tests identified by the seismic system.
- Number of earthquakes misidentified as explosions.
- Number of unidentified seismic events.

These outputs reflect the assurance and confidence verification goals respectively: the higher the percentage of militarily significant tests identified as violations, the greater the assurance of detection if deterrence fails; the fewer the numbers of unidentified seismic events and misidentified earthquakes, the greater the confidence in the treaty. Similar measures are computed by most technical analyses of the seismic monitoring options.

Technical output from the monitoring evidence component is provided in Fig. 5. Figure 5(a) shows the percent of explosions identified by seismic systems of various sensitivities. The horizontal axis represents the system sensitivity for various seismic systems, represented by medians of the probability distributions in Fig. 2. For example, a system sensitivity of magnitude 3.0 means that the system has 0.5 probability of detecting an event of magnitude 3.0. The figure illustrates a continuum of seismic monitoring capabilities, with the three options (Array, Simple, NTM) marked on the horizontal axis. Curves are provided for both cavity decoupled and fully coupled explosions of 1 and 10 kt.

Figure 5(a) clearly illustrates that detection of even 10% of decoupled low-yield (1-kt) explosions will require an extensive in-country seismic verification network, with capabilities in the range of the Array option. These results support the views of Alewine quoted earlier. Notice that fully coupled 1-kt explosions can be detected with high likelihood by all systems, and that almost all 10-kt decoupled explosions are detected by the Array system.

The results of this example highlight the need for in-country low-magnitude monitoring capabilities if (1) cavity decoupling is feasible and (2) low-yield testing is judged to be militarily or politically significant.

Figure 5(b) illustrates the problem of false alarms, which Dyson emphasized. The vertical axis estimates the number of earthquakes that would be identified incorrectly as explosions by various seismic verification systems. (In the figure these are called false alarms.) Note that the Array option would make several incorrect identifications in a single year, and that the number of false alarms increases exponentially with detection capability. The false alarm problem is further confounded by much larger numbers of unidentified events, not shown on Fig. 5(b), and the perplexing problem of discriminating between nuclear and chemical explosions.

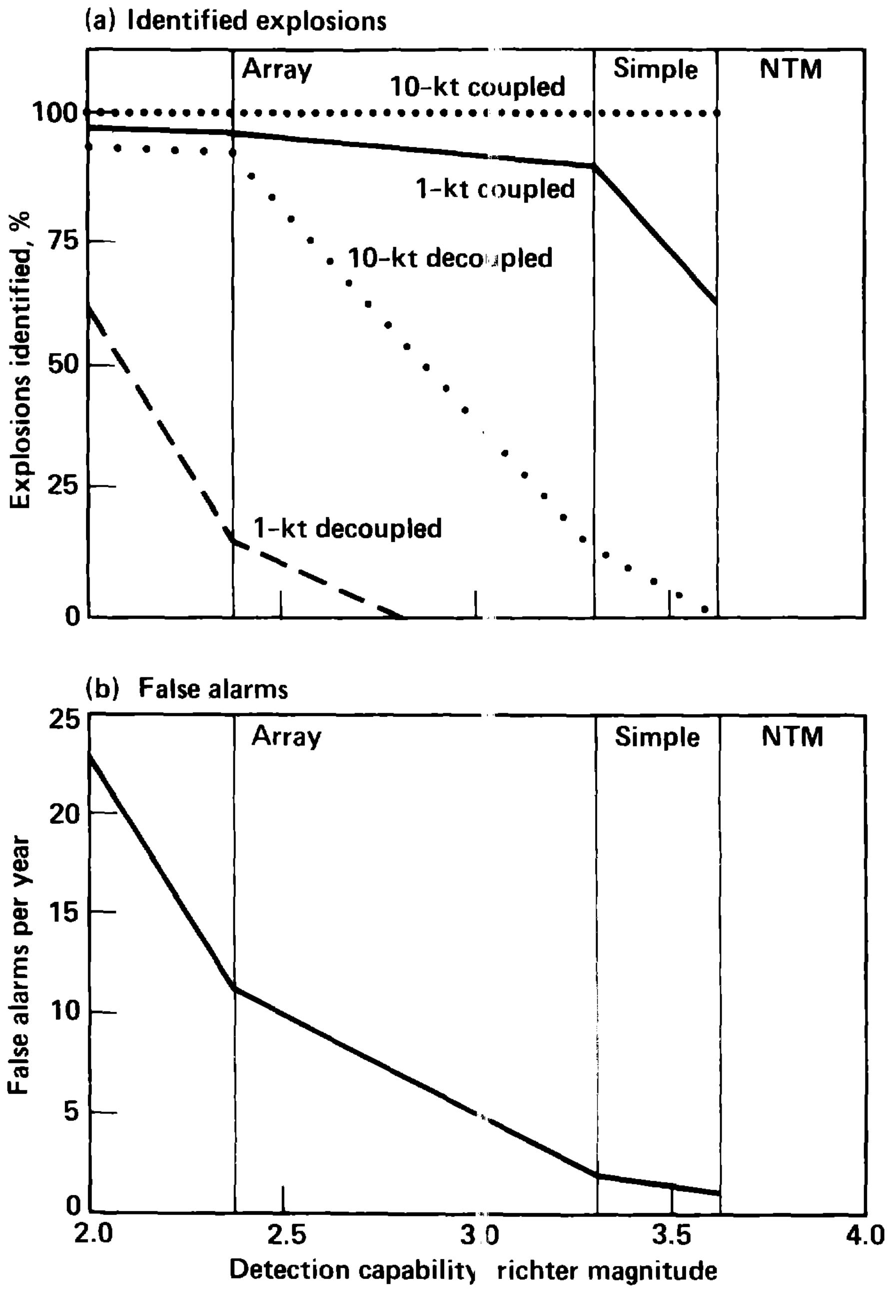


Figure 5. A fundamental verification system tradeoff between assurance that violations will be identified and building confidence by reducing false alarms. The horizontal axis measures detection capability, with sensitive systems on the left and less capable systems on the right. (a) Highly capable systems are required to detect 1-kt explosions detonated in large underground cavities (i.e., decoupled explosions). Larger and coupled explosions can be detected with less capable systems. (b) An exponential increase in false alarms occurs as system sensitivity is increased.

## OVERALL EVALUATION RESULTS

By comparing (a) and (b) of Fig. 5 one can appreciate the conflict between detection capability and false alarms, which underlies the views expressed by Dyson and Alewine. By using additional model components, one can begin to make explicit tradeoffs between detection capability and false alarms, and thereby produce an overall evaluation of verification options. For example, by expanding the analysis to include the U.S. response and Soviet action components, the user can calculate the probability of Soviet compliance with the treaty. The probability of Soviet compliance can then be used as a combined performance measure that takes into account both detection (assurance) and false alarm (confidence) considerations. This output relates directly to the deterrence goal: the greater the emphasis one places on deterrence, the better the probability of compliance can be used as a proxy for the total value of the option.

By expanding the analysis to include the evaluation component (see Fig. 1), the analyst can provide value judgments regarding the overall importance of assurance, deterrence, confidence, and cost. The model can then compute a net value to the U.S. for each verification option. This net value can, in turn, be used to provide an overall ranking of the options and, more importantly, to determine how rankings change under different assumptions and value judgments.

The primary value inputs to the determination of net value are benefit and cost judgments. Illustrative U.S. value judgments were described earlier (Fig. 4). Several different types of costs are included for each option in this illustrative analysis. These include the relative cost of installing and operating each system as well as the cost of processing seismic data.

Illustrative overall results are shown in Fig. 6. The vertical axis indicates U.S. net value, taking into account assurance, deterrence, and confidence goals as well as costs. For easy interpretation, the net value axis has been rescaled so that the current NTM capabilities have a reference value of zero.

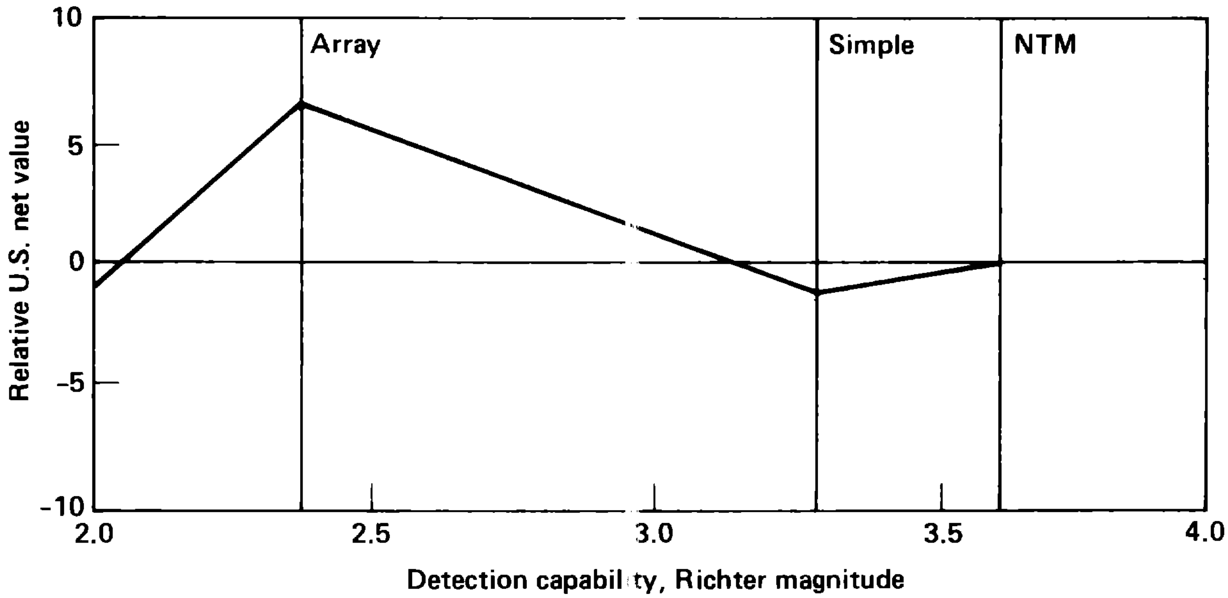


Figure 6. Variation of the overall value of the verification system with system detection capability (sensitivity) for a "base case" set of assumptions. The net-value scale has been adjusted to give the current national technical means (NTM) a value of zero for easy comparison. The Simple network is of less overall value than the NTM system because it is more expensive (and more intrusive) and only somewhat more sensitive. The Array network has a high value because its vastly improved detection capability overshadows its increased cost. However, systems with even greater detection capability have lower values than the Array network because of higher costs with improved detection only for very low-yield (e.g., 1-kt) decoupled explosions.

Beginning at the right of the figure with current NTM capabilities and moving to the left, the curve decreases at first. This is because the Simple seismic system costs more than NTM but does not substantially increase detection capabilities for cavity decoupled explosions in the 1- to 10-kt range, which in this example are the smallest tests deemed to be militarily significant. Between the Simple and Array options, the value of improved detection capabilities increases rapidly, thereby causing the "net" value curve to increase to a maximum at the Array system. However, for lower-magnitude monitoring systems, the capabilities are not substantially better than those of the Array system, except for very low-yield (e.g., 1-kt) decoupled explosions. Yet costs of the lower-magnitude systems are assumed to be greater than for the Array network, so the net value curve falls off rapidly. The implication is that for these assumptions and value judgments the Array option is optimal. However, the judgment that tests below 1 kt are not military significant strongly influences this conclusion.

We will refer to the curve in Fig. 6 as the "base case" comparison of verification options. The base case results from assumptions (e.g., the Soviet Union exploits cavity decoupling) and data and value judgments (e.g., those illustrated in Figs. 2 through 4). In the following section, we will examine the sensitivity of the results illustrated in Fig. 6 to changes in base-case data and assumptions. First, however, we summarize the results of the illustrative application of the framework.

## SUMMARY OF BASE-CASE RESULTS

The illustrative analytical results in Fig. 6 compare the relative value of alternative seismic systems ranging from systems with no internal stations to extensive in-country array systems. The monitoring challenge of detecting possible clandestine low-magnitude explosions that have been cavity-decoupled necessitates an extensive in-country seismic network. As a result, the net value of systems increases with improved detection capability until the point at which the problems of cost and numerous false alarms begin to overwhelm the benefits of improved detection and reduce the net value of the most sensitive systems. Once the systems are capable of detecting the militarily significant tests, greater detection capability is not warranted or, perhaps, even desirable.

Having the capability to produce a base-case graph (such as Fig. 6) represents an important advance in the ability to incorporate explicitly and systematically a wide range of important technical and political factors and judgments in comparing seismic verification options. However, one must bear in mind the subjective nature of several inputs to this graph. Therefore, Fig. 6 provides a useful reference for examining the sensitivity of relative rankings to changes in subjective or uncertain data elements in the model.

## 4. SENSITIVITY ANALYSIS

In this section we assess the sensitivity of the base-case results in Fig. 6 to changes in data and assumptions in the model. We noted in the introduction that any consideration of the capabilities of verification options requires interrelated technical and value judgments. The technical judgments include many estimates: e.g., seismic monitoring capabilities, auxiliary information sources, evasion possibilities, and natural seismicity. The value judgments include the military significance of clandestine testing programs or the relative U.S. and Soviet values discussed in Fig. 4.

Our first sensitivity analysis examines the importance of technical judgments in the monitoring evidence component of the model. Specifically, we examine the importance of cavity decoupling and the level of natural seismicity. The second analysis looks at a value judgment in that same component, namely the importance of judging the military significance of possible treaty violations. A third analysis explores potential improvements in our low-magnitude detection capabilities and discusses their research and policy implications.

### SENSITIVITY TO TECHNICAL JUDGMENTS

Figure 7(a) illustrates three curves each representing different technical judgments in the monitoring evidence component. The curve labeled "base case" represents the base-case results from Fig. 6. However, the scale in Fig. 7(a) has been changed to accommodate greater variations in value than the scale in Fig. 6.

#### Cavity Decoupling

Recall that in the base case we assume the Soviets will exploit cavity decoupling to conceal treaty violations. The upper curve in Fig. 7(a) shows a revised comparison of options when we assume no cavity decoupling. Comparing this curve to the base case illustrates two results. First, values are higher under the assumption of no cavity decoupling because the verification systems are assumed practically to assure detection (and therefore deterrence) of treaty violations. Relative to the base case, this

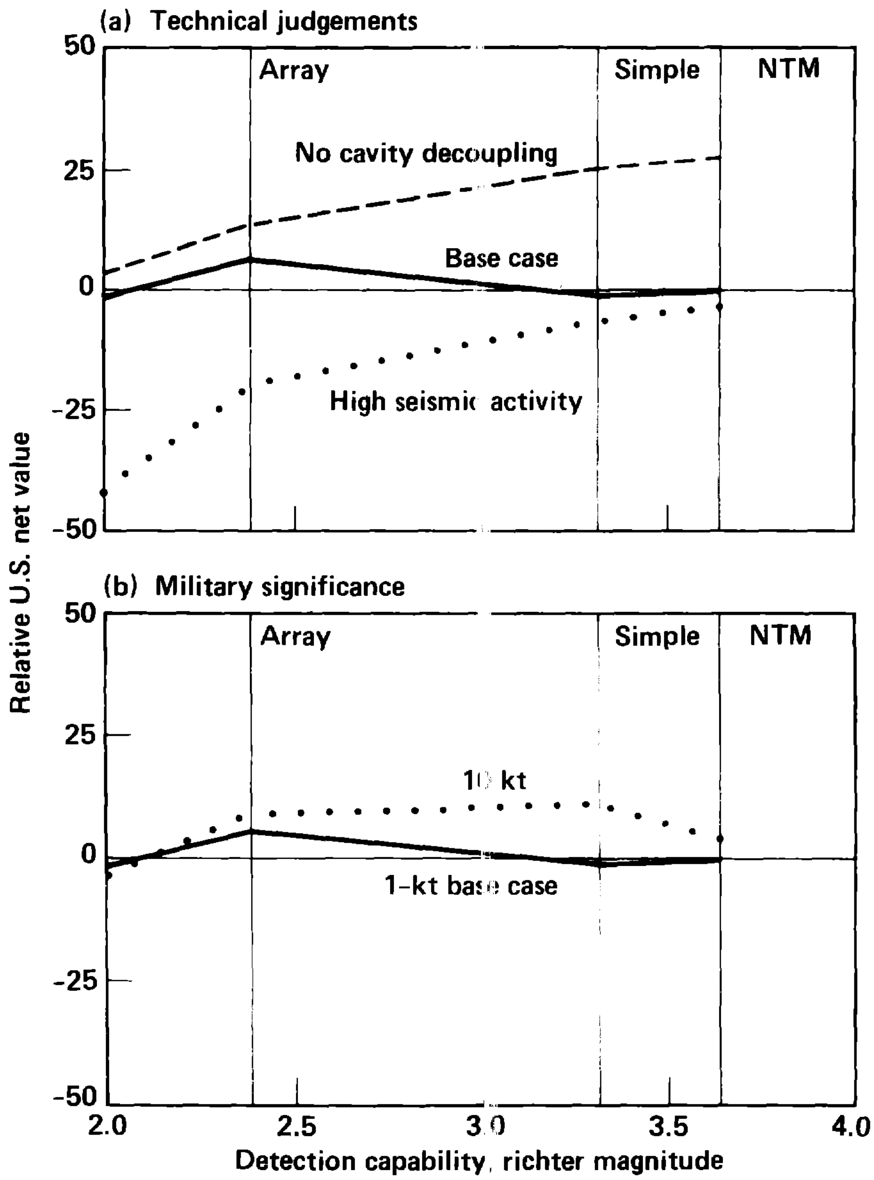


Figure 7. Sensitivity analysis showing how the relative values of the three verification options change in response to different assumptions. The vertical scale has been compressed to show the much larger range of values under these assumptions. The base case (solid black) is repeated from Fig. 6. (a) If we assume that cavity decoupling (or similar evasion techniques) are not feasible, the NTM system is the most attractive because it can detect all the militarily significant tests at no extra cost (dashed line). Also, if we assume more than three times as many small earthquakes as in the base case, the NTM system again is the most valuable because it is least liable to produce false alarms (dotted line). (b) If we decide that all test explosions smaller than 10 kt can be ignored (instead of 1 kt, as in the base case), the Simple seismic network becomes the most attractive because it provides adequate detection capability at reasonable cost.

substantially increases the likelihood of mutual treaty compliance, which is the best outcome to the U.S. (based on the U.S. values in Fig. 4).

The second result is that NTM capabilities are adequate if cavity decoupling and other evasion schemes are not viable. There is no need to take on the problems of false alarms and costs of in-country systems when NTM is virtually assured of providing adequate verification. Notice that this also implies that if either side entered the treaty assuming the other side would not resort to clandestine testing, they would feel no need for improved verification capabilities.

Natural Seismicity

The lower curve in Fig. 7(a) indicates the sensitivity to the estimates of natural seismicity in the Soviet Union. The high seismic case estimated roughly 14,000 annual seismic events of magnitude greater than [illegible].0 compared to 4,000 events of the same magnitude in the base case. Note that as before, NTM provides the most valuable verification, as opposed to the Array option in the base case. In the high-seismic case the cost of processing detected events and the negative implications of unidentified events and misidentified earthquakes (false alarms) overshadow any benefit derived from in-country monitoring capabilities. (This point is also illustrated by the fact that the high-seismic curve is always below the base case.)

In summary, these sensitivity cases highlight the importance of estimates of feasibility of cavity decoupling and the degree of natural seismicity in the Soviet Union. In the cases shown in Fig. 7(a) the new assumptions about these variables are adequate to nullify the benefits of in-country monitoring (given the other assumptions and data in the model).

SENSITIVITY TO MILITARY SIGNIFICANCE OF VIOLATIONS

In the base case, we assume that a 1-kt test is the lowest-magnitude of military or political significance. Figure 7(b) compares the base case to an assumption that there is no detrimental impact on the U.S. if the Soviets violate the treaty with yields up to

10 kt. Since we saw in Fig. 5(a) that the limit of the Simple system detection capabilities is clandestine (decoupled) tests of approximately 10 kt, it is no surprise that the Simple system now has the highest value Note also that the 10-kt case is always of greater value than the base case because we are more likely to detect the larger tests for any seismic system, and therefore more likely to deter violations.

## SENSITIVITY TO U.S. INTERPRETATION OF AND RESPONSE TO EVIDENCE

As we saw in Fig. 5(a), the Array system identified about 15% of low-magnitude (1-kt) explosions, but also misidentified several earthquakes as explosions, as was illustrated in Fig. 5(b). The results seen in Figs. 5-7 suggest that for this kind of low-magnitude monitoring, improvements are needed to deal with the false alarms. Without those improvements, low-magnitude monitoring might lead to an unacceptably high likelihood of inappropriate responses by the U.S. to evidence of Soviet violations. Therefore, we evaluated several potential improvements to the Array-type verification system and in the process generated several useful insights.

### Event-Count Interpretation of Evidence

Recall the input figure for the U.S. Response model, Fig. 3, which showed the probabilities of the U.S. taking strong, mild, or no action as a function of the strength of monitoring evidence. The method used for evaluating and interpreting evidence from the monitoring system must be selected carefully. For example, one might judge the strength of the evidence simply by counting the number of apparent violations over a given period of time (we use one year). We will call this the "event-count" approach. In this case the horizontal axis in Fig. 3 would be "number of events identified seismically as explosions." A more restrictive requirement would be to demand supporting auxiliary evidence before an event could be counted as evidence.

Figure 8 shows four sensitivity cases, and one of them is labeled "event-count." The horizontal axis has the same measure of the detection capability of verification options as the earlier figures, although the vertical axis has a new measure of effectiveness--the probability of the U.S. taking strong action even though the Soviet

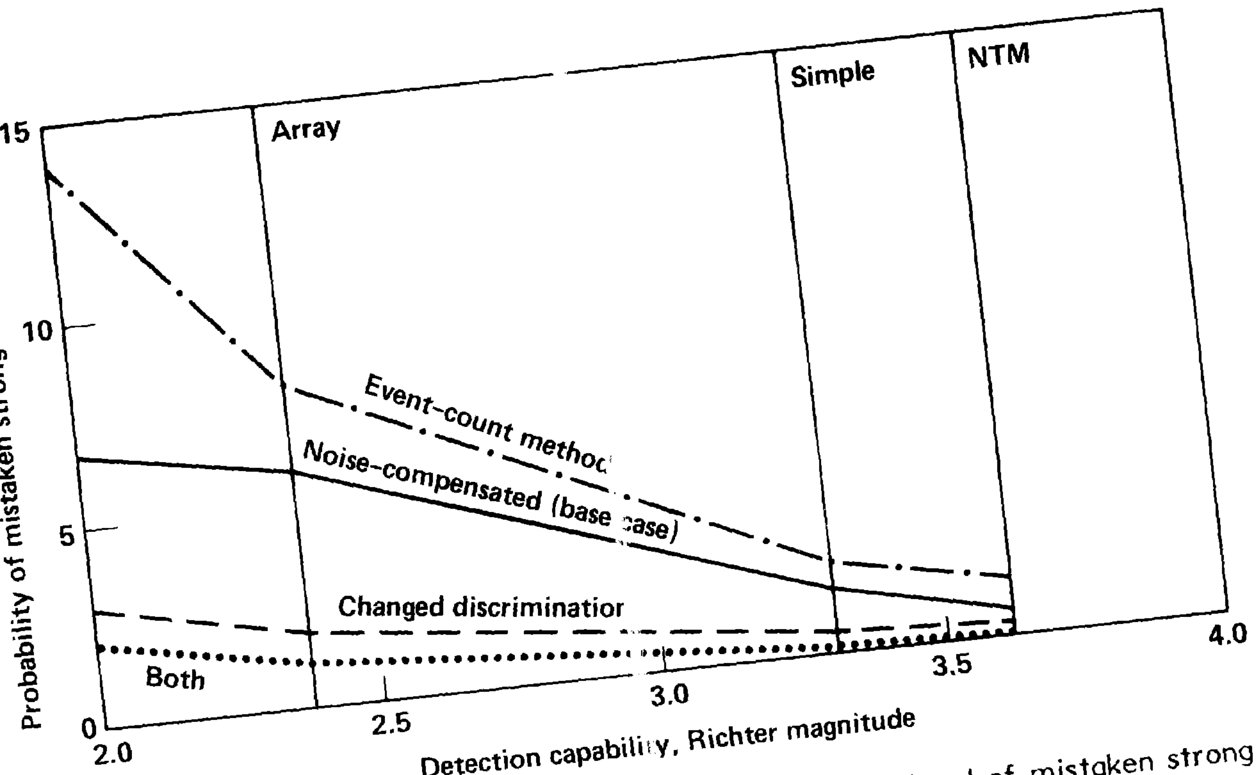


Figure 8. The effect of various changes to reduce the likelihood of mistaken strong action on the part of the U.S. The event-count method (dot-dash line) indicates a violation when, in a given period of time, the number of events of various magnitudes becomes excessive. A method of interpreting the evidence that compensates for noisy conditions at small magnitudes reduces the probability of inappropriate responses to false alarms (solid line). Changing the discrimination criteria to allow for the large numbers of innocent small shocks also reduces the number of false alarms (dashed line). Combining the two changes produces the fewest false alarms (dotted line).

Union is complying with the treaty. In an ideal verification system, this probability of inappropriate U.S. response would be zero.

Notice that when the strength of evidence of a violation is measured using the event-count approach, the systems such as the Array, with low-magnitude detection capabilities, have higher probability of inappropriate action than do the less capable Simple and NTM systems. This is because substantial natural seismicity at low magnitudes would generate several events that appeared to be (and are counted as) explosions, even though they are actually earthquakes. Under the event-count approach, sufficient counts would trigger a strong U.S. response even given Soviet compliance. (Although not shown in Fig. 8, the ultimate result is reduced likelihood of Soviet compliance and, hence, a reduction in overall system value for the extremely sensitive seismic systems.)

A fruitful area of improvement in our capability to deal with false alarms is the measurement of the strength of evidence. The simple event-count approach used above is based directly on events identified as explosions. The difficulty is that not every event that appears to be a violation is a violation, and not all violations are equally severe. An alternative response model can be formulated that is based on some measure of confidence in the evidence.

Noise-Compensated Interpretation of Evidence

In the decision analysis model we have developed and incorporated a method of interpreting evidence that compensates for noisy conditions at low magnitudes. This interpretation of evidence is used to determine the base-case results in Figs. 6 and 7. The U.S. response in this formulation is based on estimates of the probability that the evidence cannot be explained by natural seismicity (or "noise"). When this probability is low, then the probability of strong U.S. action is high.

The results using this noise-compensated response model are shown with the noise-compensated curve in Fig. 8. The noise-compensated model clearly reduces the inappropriate responses to false alarms under the conditions of Soviet compliance.

Further calculations using the model indicate that a relatively stable political situation is possible: i.e., the probability of Soviet compliance is high and the U.S. political response system has a relatively low false-alarm rate

Changed Discrimination Rule

An alternative approach to reducing false alarms due to low-magnitude seismicity is to change the criteria for deciding whether events are earthquakes or explosions. Typically, the criteria are established through statistical procedures using data from known sources (earthquakes and explosions). Often, the statistical procedures attempt to balance the likelihood of misinterpreting earthquakes and explosions.

Since low-magnitude detection systems are likely to be confronted with many more earthquakes than explosions at low magnitudes, the setting of the criteria may not be appropriate. Using the decision analysis model, we evaluated a sensitivity case postulating radical changes to the criteria for discriminating between explosions and earthquakes. The revised tradeoff recognizes the large numbers of natural seismic events, and therefore lowers the probability of identifying an earthquake as an explosion. As a consequence, the probability of the other type of error--falsely identifying an explosion as an earthquake--is increased.

The curve labeled "changed discrimination rule" in Fig. 8 shows the results of this alteration. Note that this has about the same effect on reducing the likelihood of an inappropriate U.S. response as the noise-compensated approach to interpreting evidence. However, when both changes are combined, the probability of a mistake is reduced substantially relative to the initial event-count case.

Figure 9 compares the sensitivity of the relative U.S. value to these improvements in U.S. response rules in a manner similar to the other sensitivity cases in Figs. 7(a) and 7(b). Note that relative U.S. value is not as sensitive to the changes in Fig. 9 as in Figs. 7(a) and 7(b), but that all the different U.S. response rules lead to the same conclusion regarding the superiority of the Array-type system for low-magnitude monitoring. However, both the noise-compensated interpretation of evidence and the

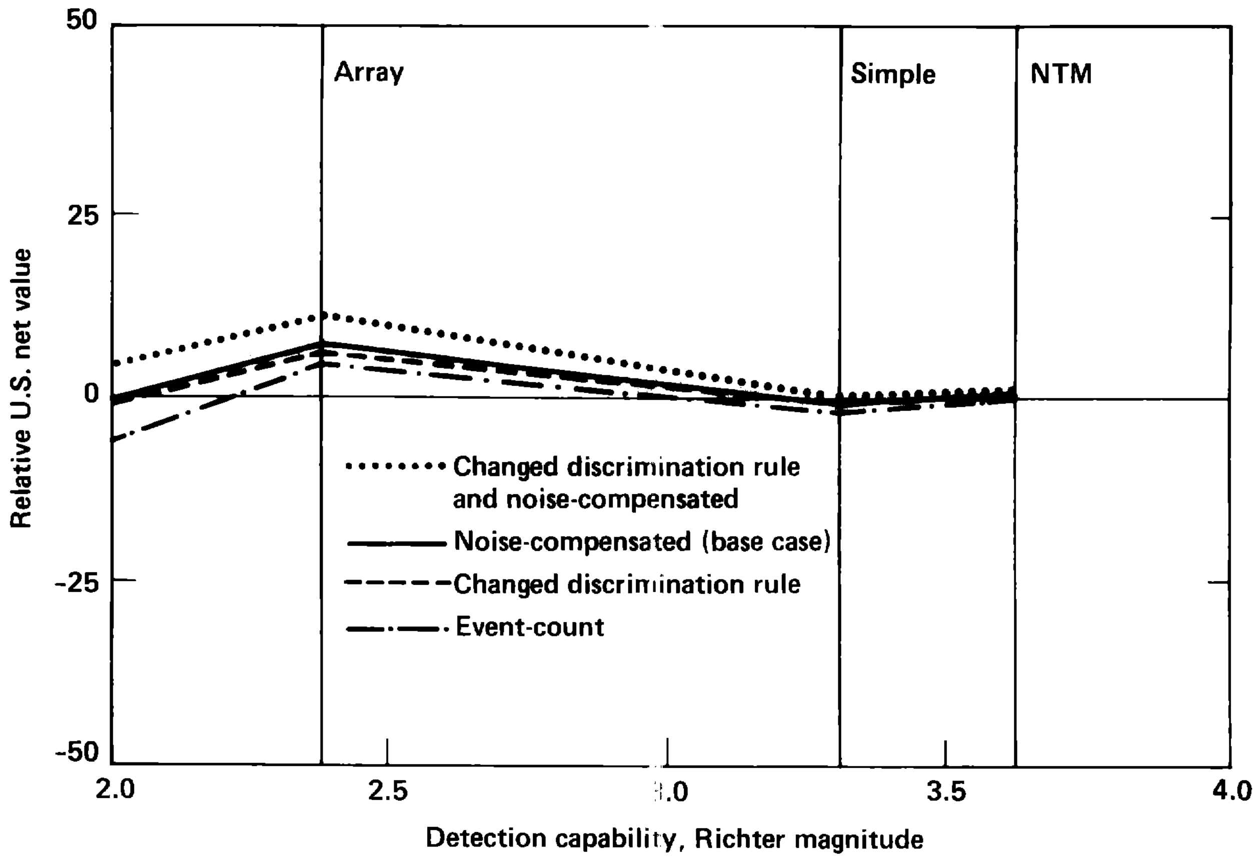


Figure 9. U.S. value is sensitive to the U.S. interpretation of and response to evidence. By using a noise-compensated interpretation of evidence or by changing the criteria for classifying seismic events as nuclear explosions, the U.S. can increase over a simple event-counts interpretation its relative net value for all levels of detection capability. Both of these approaches reduce the number of false alarms (Fig. 8), but the noise-compensated interpretation does so without screening out true violations. By decreasing inappropriate U.S. responses, the probability of Soviet compliance is increased.

changed discrimination rules increase the net value over the event-count rule for all seismic systems. This results primarily from a reduction in inappropriate U.S. responses, thereby increasing the probability of Soviet compliance. This can lead to a more stable treaty environment.

On-Site Inspections

Many versions of a CTBT that have been considered will permit some form of on-site inspections (OSIs) of suspected nuclear explosions. Accordingly, our framework reflects the interaction between OSIs and other monitoring evidence, including seismic and auxiliary evidence. OSIs can confirm a nuclear explosion, provide evidence of a seismic event other than a nuclear explosion, or provide no evidence. If an OSI confirms a nuclear explosion or supports the classification of an event as an earthquake, this evidence is assumed to overwhelm all other monitoring evidence. The role of on-site inspections in verification must be clearly defined and explained in order to avoid diminishing the net value of a verification system. For example, one view might hold that the U.S. could not take strong action without positive evidence from an OSI, irrespective of the strength of evidence from other sources. An alternative view might be that evidence from OSIs is sufficient but not necessary for action. Figure 10 shows the impact of the first viewpoint on the base case results. Requiring a confirmatory OSI before responding to evidence greatly reduces the net U.S. value. This result reflects the judgments by experts who believe that on-site inspections have a low probability of detecting evasion. By requiring OSI evidence prior to responding, the Soviet Union is allowed more leeway for clandestine nuclear tests without an appropriate U.S. response.

While these results illustrate the importance of proper treatment of OSI data in the U.S. decision process, they neglect two vitally important aspects of OSIs that bear directly on the overall capability of a verification system. First, a CTBT may be structured so that OSIs are not necessarily accusatory but are used for building confidence. Such a treaty may specify a minimum number of OSIs per year and thereby allow the use of OSIs to resolve potential false alarms. Second, and perhaps more importantly, the threat of an OSI is regarded as a deterrent in that it increases the cost of evasion, increases evader uncertainty, and in general limits the benefits from any

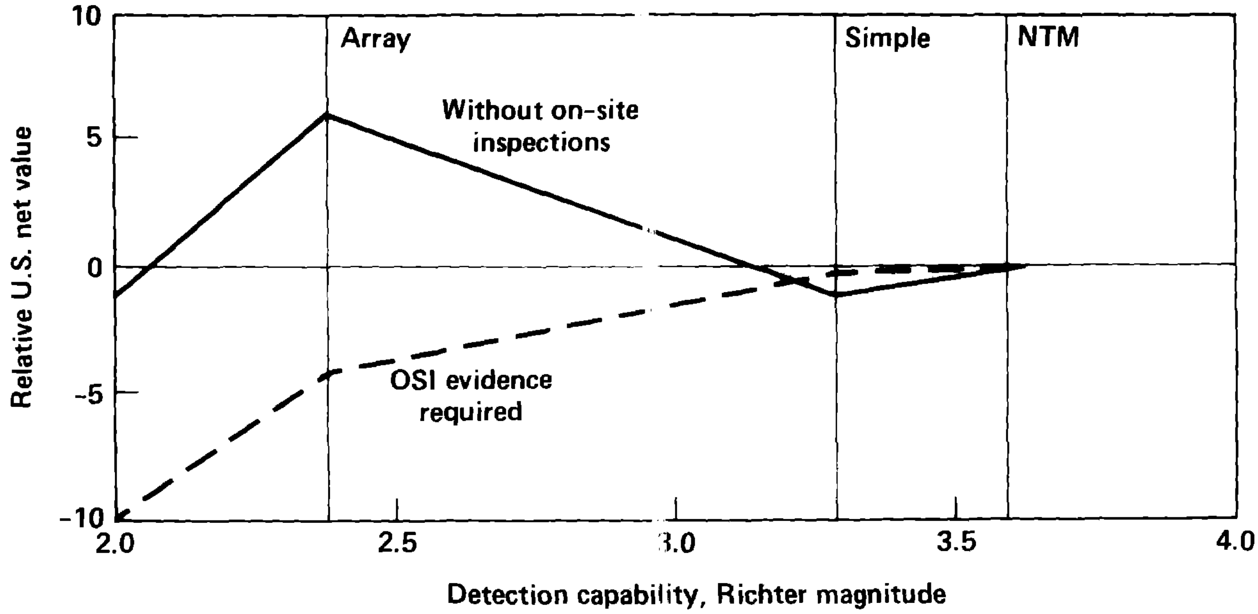


Figure 10. Requiring an on-site inspection (OSI) to confirm a Soviet nuclear explosion in violation of a CTBT reduces the relative U.S. net value. The base case (solid black), without on-site inspections, is repeated from Fig. 6. If the U.S. cannot respond to evidence of Soviet violations without confirmatory evidence from on-site inspections, relative net U.S. value is lower (dashed line) for all but the least capable seismic verification systems. Such a strict evidence requirement allows the Soviet Union extra leeway for clandestine testing without an appropriate U.S. response.

possible clandestine testing program. Our framework and computer model were not designed to investigate either of these aspects of OSIs, and therefore we do not provide insights or conclusions in these areas.

## SUMMARY OF INSIGHTS REGARDING LOW-MAGNITUDE SEISMIC MONITORING

While only illustrative, the analysis presented in this and the preceding sections does produce several insights into the CTBT verification problem. First, as long as cavity decoupling is regarded as a plausible scenario for clandestine testing, a highly capable network of internal seismic stations will be required. Second, the networks proposed to meet this requirement are more extensive than systems considered several years ago. However, the value of the highly capable network is potentially compromised by the threat of false alarms and the ambiguity of unidentified events.

Technological advances, particularly in the areas of event discrimination and processing procedures for large numbers of events, can improve the situation, but these improvements, due to increased noise, are only partial solutions to the verification problem. Preliminary analysis suggests that near perfection is required if reliance is placed on technological restrictions alone. A procedure for responding to evidence that takes into account the noise levels encountered at low magnitudes can be designed that leads to deterrence and stability.

A third important insight is that there will always be residual uncertainty on the part of the monitoring party; i.e., there is some level of testing that could be carried out under this system without detection or response. A critical component of any CTBT evaluation must be the joint consideration of verification capabilities and levels of militarily significant testing.

Additionally, the analysis makes clear that any evaluation of the ability to verify a CTBT must include all aspects of the verification system: interpretation and response procedures, technical aspects of the systems, and the manner in which the evidence is integrated. Improvements in one part of the system, such as the ability to detect low-magnitude events, can be counterproductive unless other aspects of the system, including the basis for making response decisions, are similarly improved.

Having the capability to complete such an integrated analysis allows one to test the sensitivity of the conclusions to several subjective judgments. The integrated analysis allows one to determine the differences of opinion that matter most and to focus attention on resolving them.

# 5. CONCLUSIONS

In-country seismic verification systems are designed to help verify compliance with future treaties limiting or banning nuclear weapons testing. We have developed an analytic evaluation framework that provides a systematic approach for specifying verification options, determining the benefits they provide, and balancing their benefits with impacts such as cost or intrusiveness. The framework extends earlier technical assessments by considering seismic system capabilities in a broader context, taking into account other forms of monitoring evidence, U.S. responses to evidence, and the interaction between U.S. and Soviet decision-making. The framework can be used to evaluate various seismic systems, alternative treaty provisions related to seismic verification, and research and development directed toward improving verification capabilities.

## FUTURE DIRECTIONS

The analysis to date has confirmed several important topics that earlier technical studies have identified as needing future research. These include: event discrimination at low magnitudes, potential evasion by cavity decoupling, high-frequency monitoring capabilities, background seismicity in the Soviet Union, and procedures for processing relatively large numbers of events. The importance of these technical issues is clear. Very low false alarm rates are required for political stability given postulated (and credible) levels of background seismicity. In order to assess whether widespread opportunities for evasion via cavity decoupling exist in the Soviet Union, we need (1) detailed evaluation of the feasibility of cavity decoupling and (2) more knowledge of the strength and spectrum of the signal produced. In order to assess whether the high-frequency detection method provides a technological solution for either the cavity decoupling or false alarm problem, the method needs to be evaluated rigorously with respect to assumptions about noise levels, propagation efficiency, and discrimination potential. Finally, background seismicity levels need to be estimated accurately in order to assess the information load on the monitoring system as well as to provide input to event interpretation procedures.

In addition, the analysis has identified equally important considerations related to the evaluation and interpretation of evidence from the monitoring system. These considerations include methods for integrating diverse monitoring evidence, decision rules for separating explosions from natural seismic events (and making judgments about treaty compliance or violation), protocols for dealing with anticipated large numbers of chemical explosions that cannot be discriminated from low-yield clandestine nuclear tests, and procedures for interpreting and responding to monitoring evidence generated under noisy monitoring conditions.

The analysis also highlights the importance of rigorous evaluation of the possible impact of violations. While the analysis has identified verification systems that encourage compliance and political stability, there remains some level of clandestine testing that could be undertaken. These potential violations need to be evaluated with respect to: short-term military significance; political impact; and, most importantly, long-term significance, including the impact of a treaty breakdown after some period of time.

## DECISION ANALYSIS DEVELOPMENT

We are currently expanding the scope of the decision analysis framework to consideration of the Low-Yield Threshold Test Ban Treat (LYTTBT). In this work we are examining several additional issues and developing quantitative models to analyze:

- o The relative U.S. and Soviet values of underground testing at various yield levels.
- o The benefits of limiting testing to those levels.
- o Uncertainties associated with verification of a LYTTBT, both on and off testing sites.

We are also developing a workshop to train potential users of the CTBT model and to demonstrate the usefulness of the decision analysis approach to various members of the verification community.

## 6. ACKNOWLEDGMENTS

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## 7. REFERENCES


1. R. A. Alewine, "Seismic Sensing of Soviet Tests," DEFENSE/85, 11-21, American Forces Information Service, Arlington, VA (1985).

2. F. J. Dyson, Weapons and Hope (Harper and Row, New York, 1984).

3. J. F. Evernden, "Study of Seismological Evasion, Part I. General Discussion of Various Evasion Schemes," Bull. Seism. Soc. Amer. 66 (1), 245-280 (1976a).

4. J. F. Evernden, "Study of Seismological Evasion, Part II. Evaluation of Evasion Probabilities Using Normal Microseismic Noise," Bull. Seism. Soc. Amer. 66 (1), 281-324 (1976b).

5. J. F. Evernden, "Study of Seismological Evasion, Part III. Evaluation of Evasion Possibilities Using the Code of Large Earthquakes," Bull. Seism. Soc. Amer. 66 (2), 549-592 (1976c).

6. J. F. Evernden, Science 228, letter to the editor, 792-794 (1985).

7. J. F. Evernden, C. B. Archambeau, and E. Cranswick, "An Evaluation of Seismic Decoupling and Underground Nuclear Test Monitoring Using High Frequency Seismic Data," Rev. Geophys. 24 (2), 142-215 (1986).

8. W. J. Hannon, "Seismic Verification of a Comprehensive Test Ban," Energy and Technology Review (UCRL-5200-83-5), 50-65 (1983).

9. W. J. Hannon, "Seismic Verification of a Comprehensive Test Ban," Science 227, 251-161 (1985a).

10. W. J. Hannon, Science 228, letter to the editor, 792-794 (1985b).

11. W. J. Hannon, The Value of In-Cou try Seismic Monitoring Systems, Lawrence Livermore National Laboratory, Live more, CA, UCRL-95242 Preprint, presented at SIPRI/CLIPS Study on a Comprehe sive Test Ban, Ottawa, Canada, Oct. 23-25, 1986.

12. R. A. Scribner, T. J. Ralston, anc W. D. Metz, The Verification Challenge: Problems and Promise of Strate ic Nuclear Arms Control Verification, (Birkhauser, Boston, 1985).

13. R. S. Strait and A. Sicherman, Comprehensive Test Ban Treaty Seismic Verification Decision Analysis Com uter Model, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20 04 (1986).

14. L. R. Sykes and J. F. Evernden, "Th Verification of a Comprehensive Test Ban," Sci. Amer. 247 (4), 47-55 (1982).

15. L. R. Sykes, J. F. Evernden, and I. Cifuentes, "Seismic Methods for Verifying Nuclear Test Bans," in Conf. Proc. o. 104 (American Institute of Physics, New York, 1983), p. 85-133.

16. E. Teller, "The Case for Continuin Nuclear Tests," Headline Series No. 145 (Foreign Policy Association, World Af airs Center, New York, Jan-Feb 1961).

17. S. Weisburd, "Policing the Peace: V rifying a Comprehensive Test Ban," Science News 128, 282-285 (1985).

18. H. York, "Bilateral Negotiations and he Arms Race," Sci. Amer. 249 (4), 149-160 (1983).


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